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Life cycle assessment in the construction sector: A review

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ABSTRACT

The last decades, lowering the ecological impact of buildings is receiving increased attention by researchers, policy-makers and companies. Mostly the focus is on reducing energy consumption and the use of eco-friendly materials, but the concept of life-cycle thinking is growing in importance. This paper tries to give an overview of the current situation of Life cycle assessment (LCA) in the construction industry, both of regulatory developments and academic case studies. After a short history of LCA, the focus is on LCA methodology, new standards and frameworks and an extensive selection of recent case studies.

Despite some inherent limitations of LCA as an analytic tool and fundamental differences between the individual cases, still some common trends can be indicated. In standard buildings, the use phase contributes up to 90% of the total environmental burdens, mainly due to heating and/or cooling. Due to regulations, new buildings become more energy efficient, and thereby other phases of the life cycle gain in importance e.g., choice of materials, construction, end-of-life and water use. These research topics deserve more attention, together with economic issues, the improvement of data quality and implementation of probability density distributions.

Contents

1. Introduction

In our society buildings are omnipresent, but inevitably they entail negative consequences from an environmental point of view. During their lifespan, they consume plenty of resources and energy, occupy land and eventually they are demolished. As the interest in environmental issues is rapidly growing, also within the construction industry, more attention is being paid to sustainable housing technologies and construction methods. This general increasing awareness led to the Kyoto-protocol, an international agreement on reducing the emission of greenhouse gasses and global warming [1]. In the construction sector, this resulted for instance in regulations to decrease energy consumption of dwellings and consequently their ecological burdens i.e., the Energy Performance of Buildings Directive 2002/91/EC (EPBD, 2003) and the revised EPBD 2010/31/EU issued by the European Union [2,3]. Such regulations make sense as for example in

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Flanders households have a share 36–40% of the total energy consumption, and the residential sector in Belgium produces about 40% of the emitted CO_2 [4,5]. The European regulations stimulated the emergence of new building concepts such as low-energy and even self-sufficient houses [6,7]. When only focusing on energy consumption, low-energy houses excel compared to standard houses [8].

But besides energy consumption, also other aspects affect the sustainability of buildings, a concept that covers ecological, economic and social aspects. With the increasing awareness of these issues, plenty of tools have been developed to asses sustainability from different viewpoints and for a variety of users [9]. Some examples are Environmental Impact Assessment (EIA), System of Economic and Environmental Accounting (SEEA), Environmental Auditing and Material Flow Analysis (MFA). In addition, several methods have been developed specifically for the construction sector such as BREEAM and LEED, which provide measurement ratings for (green) buildings. A discussion on all these tools is beyond the scope of this review that will focus on Life Cycle Assessment (LCA), because this is commonly used and much more detailed compared to rating tools. LCA is a tool to investigate environmental burdens of a product or process, considering the whole life cycle, from cradle to grave [10]. All aspects considering natural environment, human health and resource depletion are taken into account and together with the life cycle perspective, LCA avoids problem-shifting between different life cycle stages, between regions and between environmental problems.

2. A brief history

The first studies on environmental impacts date from the 1960s and 1970s, focusing on the evaluation or comparison of consumer goods, with only a small contribution to the use phase [11]. According to Guinée et al. one of the first (unpublished) studies was executed by Midwest Research Institute (MRI) for The Coca Cola Company in 1969, including resources, emission loadings and waste flows for different beverage containers [11]. In the beginning of the 1980s, life cycle thinking appears in the construction sector with a study of Bekker, with focus on the use of (renewable) resources [12]. These early researches applied diverging methods, approaches, terminologies and results. There was a clear lack of scientific discussion and

Table 1

RECENT CASE STUDIES Author	Year	Country	Cases	Type build.	Type	Impact method	Lifespan	Prod.	Use	EoL	Sens.	Transp.
Adalberth [55]	1997	Sweden	3	R	LCEA	Cum. En.	50	x	x	x	-	x
Adalberth et al. [56]	2001	Sweden	4	R	scr. LCA	Midpoints (SBID)	50	x	x	x	x	x
Allacker [57]	2010	Belgium	16	R	LCA	External Costs	60	x	x	x	x	x
Arena and Rosa [58]	2003	Argentina	2	S	scr. LCA	Midpoints (SBID)	50	x	x	-	-	x
Asif et al. [59]	2007	Scotland	1	R	LCEA	Cum. En.	?	x	-	-	-	-
Audenaert et al. [60]	2012	Belgium	1	R	LCA	Eco-Ind.99	?	x	x	x	-	-
Blanchard and Reppe[61]	1998	USA	2	R	LCEA	Cum. En.+GWP	50	x	x	x	x	x
Blengini and Di Carlo [43]	2009	Italy	2	R	LCA	Midpoints+Eco-Ind.99+EF +EPS2000	70	x	x	x	-	x
Blengini[62]	2009	Italy	1	R	LCA	Midpoints+Eco-Ind.99	40	x	x	x	x	x
Chen and Burnett [63]	2001	China	2	R	LCEA	Cum. En.	40	x	-	x	-	x
Citherlet and Defaux [64]	2007	Switzerland	3	R	LCA	CML 2	?	x	x	x	x	x
Cole and Kernan [65]	1996	Canada	12	O	LCEA	Cum. En.	50	x	x	x	x	?
De Meester et al. [66]	2009	Belgium	65	R	LCEA	Cum. Exergy	75	x	x	x	-	x
Dewulf et al. [67]	2009	Belgium	1	R	LCEA	Cum. Exergy	50	-	-	x	x	x
Erlandsson and Levin [68]	2005	Sweden	1	R	LCA	BYKR	35	x	x	-	-	-
Fay et al. [69]	2000	Australia	2	R	LCEA	Cum. En.	100	x	x	-	x	x
Gerilla et al. [70]	2007	Japan	2	R	LCA	Midpoints+External costs	35	x	x	x	x	x
Guardigli et al. [71]	2011	Italy	2	R	LCA	Eco-Ind.99	?	x	-	-	-	x
Huberman and Pearlmutter [72]	2008	Israel	1	R	LCEA	Cum. En.+GWP	50	x	x	-	-	x
Junnila [73]	2004	Finland	1	O	LCA	Midpoints	50	x	x	x	-	x
Kofoworola and Gheewala [74]	2008	Thailand	1	O	LCA	Midpoints	50	x	x	x	-	x
Marceau and VanGeem [75]	2006	USA	2	R	LCA	Eco-Ind.99 +EDIP96+EPS2000	100	x	x	-	x	x
Mithraratne and Vale [76]	2004	New Zeeland	3	R	LCEA	Cum. En.	100	x	x	x	-	x
Ortiz et al. [77]	2009	Spain	1	R	LCA	CML 2	50	x	x	-	x	x
Ortiz et al. [78]	2010	Spain - Colombia	2	R	LCA	CML 2	50	x	x	x	x	x
Peuportier[47]	2001	France	3	R	LCA	CML 1 (+ extra indicators)	80	x	x	x	x	x
Reddy and Jagadish[79]	2003	India	3	R	LCEA	Cum. En.	?	x	-	-	-	x
Rosa and Aqisa [80]	2012	UK	3	R	LCA	CML 2	50	x	x	x	x	x
Rossi et al. [81]	2012	Belgium	2	R	LCEA	Cum. En.+GWP	50	x	x	x	-	x
Scheuer et al. [82]	2003	USA	1	S	LCA	Midpoints+Cum. En.	75	x	x	x	-	x
Suzuki and Oka [83]	1998	Japan	10	O	LCEA	Cum. En.+GWP	40	x	x	-	-	-
Thormark [45]	2000	Sweden	2	R	LCA	Eco.Scar.1990+EPS1992+ET1992	?	x	-	x	x	x
Thormark[84]	2002	Sweden	1	R	LCEA	Cum. En.	50	x	x	x	x	x
Thormark [85]	2006	Sweden	1	R	LCEA	Cum. En.	50	x	x	x	x	x
Winther and Hestnes	1999	Norway	5	R	LCEA	Cum. En.	50	x	x	-	-	x
Wu et al. [86]	2011	China	1	O	LCEA	Cum. En.+CO_2	50	x	x	x	-	x
Xing et al.[87]	2008	China	2	O	LCA	Midpoints	50	x	x	?	-	-
Zimmermann et al. [88]	2005	Switzerland	–	All	LCA	Eco.Scarc.1990+GWP+2000 W soc.	?	x	x	-	-	x

R=Residential, O=Office, S=School, x=Included, -=Excluded,?=Unknown, Cum. En.=Cumulated Energy, EF=Ecological Footprint, GWP=Global Warming Potential, BYKR=Swedish Building Eco-Cycle Council.

consensus and the technique was often used for market claims with doubtful results, which prevented LCA from becoming a generally accepted and applied analytical tool [13].

In the 1990s came a period of standardization, with the organization of workshops and the publication of several handbooks and scientific papers [13–18]. From this decade, the Society of Environmental Toxicology and Chemistry (SETAC) started playing a leading and coordinating role by bringing the LCA practitioners together and harmonizing the framework, methodology and terminology, which resulted in the SETAC 'Code of Practice' [19]. From 1994 the International Organization for Standardization (ISO) was involved as well, whose main achievement has been the harmonization of methods and procedures, resulting in the ISO 14040 standard series, first published in 1997 [20]. The result of this standardization was the creation of a general methodological framework, which made it easier to compare different LCAs. It is important to keep in mind that even with the consensus on the framework, ISO never aimed at defining the exact methods by stating 'there is no single method for conducting LCA' [10].

From the start of the 21st century, interest in LCA has been increasing rapidly, as can be seen in the overview of case studies in Table 1. Life cycle thinking is also growing in importance within European Policy as i.e., demonstrated by the Communication from the European Commission on Integrated Product Policy (IPP) [21]. A direct result of the IPP is the development of the International Reference Life Cycle Data System Handbook (ILCD), a practical guide for LCA according to the current best practice published in 2010, complementary with the ISO 14040 series [22–24].To facilitate the use of LCA and to improve supporting tools and data quality, the United Nations Environment Program (UNEP) and SETAC launched the Life Cycle Initiative [25,26]. Another indication of the growing importance of life cycle thinking is the emergence of Environmental Product Declarations (EPDs) [27,28]. An EPD is a set of quantified environmental data for a product with pre-set categories of parameters based on the LCA standards (ISO 14040 series) and additional environmental information is not excluded. This system makes it easier for designers to choose for eco-friendly products or materials [29].

In the last decade, there have been also some developments specifically targeting the construction sector, in addition to the ISO 14040 standards. In 2003, SETAC published a state-of-the-art report on Life-Cycle Assessment in Building and Construction, an outcome of the Life Cycle Initiative [30]. This study highlights the differences between the general approach of LCA and LCAs of buildings. Such standardization continued, with two leading organizations, the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN). The first, more specifically the ISO Technical committee (TC) 59 '*Building Construction*' and its subcommittee (SC) 17 '*Sustainability in Building construction*', published four standards describing a framework for investigating sustainability of buildings and the implementation of EPDs [31]. The CEN Technical Committee (TC) 350 '*Sustainability of construction works*' is developing standards for assessing all three aspects of sustainability (economical, ecological, social) both for new and existing construction works and for facilitating the integrating of EPDs of construction products [32]. Since these standards are very recent, only very few studies have been executed according to them.

3. LCA methodology

As described in the previous section, in current practice LCAs are executed according to the framework of the ISO 14040 series [10]. To analyze the environmental burdens of processes and products during their entire life cycle, four steps have to be run through, making it possible to compare different studies: goal and scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and an interpretation [33–36].

The first step, goal and scope, defines purpose, objectives, functional unit and system boundaries. One of the strengths of LCA is defining investigated products and processes based on their function instead of on their specific physical characteristics. This way, products can be compared that are inherently different, but fulfill a similar function e.g., paper towels versus reusable cotton towels for drying hands. The second step (LCI) consists of collecting, as well as describing and verifying, all data regarding inputs, processes, emissions, etc. of the whole life cycle. Third (LCIA), environmental impacts and used resources are quantified, based on the inventory analysis. This step contains three mandatory parts: selection of impact categories depending on the parameters of goal and scope (where the authors insist on a maximization approach), assignment of LCI results to the selected impact categories (classification) and calculation of category indicators (characterization). In the current practice there is a large set of impact categories commonly used, for example global warming potential (GWP), but ISO 14044 states that when the existing categories are not sufficient, new ones can be defined [34]. The LCIA step also contains two optional steps: normalization and weighting. Normalization is the calculation of the magnitude of category indicator results relative to some reference information, for example the average environmental impact of a European citizen in one year. Weighting is the process of converting indicator results of different impact categories into more global issues of concern or a single score, by using numerical factors based on value-choices, for example based on policy targets, monetarisation or panel weighting—the authors emphasize the fact that this is the first and major step in a LCA where non-objective measures come in. This is part of the environmental mechanism (see further). The fourth and final step is the interpretation of the results [10,34].

The approaches to calculate environmental impacts can be subdivided into two types, attributional and consequential LCA. Attributional LCA is defined by its focus on describing the environmentally relevant flows within the chosen temporal window, while consequential LCA aims to describe how environmentally relevant flows will change in response to possible decisions [37,38]. Generally, most authors state that consequential LCAs are more appropriate for decision-making, unless their uncertainties in the modeling outweigh the insights gained from it [39,40]. When LCA is used to indicate hotspots of the environmental burdens as base for improvements, the consequences of these implementations should not be neglected. Such actions will influence the production of upstream products, other life cycles and more in general, other economic activities. Both positive and negative mechanisms can occur. If efficiency measures are profitable, economic activities may increase and diminish the environmental benefits. This negative mechanism is also called a rebound effect [41]. A positive mechanism is that investments in emerging technologies are likely to reduce manufacturing costs, which can trigger similar investments of other manufacturers [38]. If such a new technology has a lower impact, this can entail huge savings for the entire society and in that case a consequential approach is more appropriate.

Although ISO standards describe the global framework of an LCA, the exact technique to calculate environmental impacts is not defined. Depending on the nature of research, different methods can be chosen, defined by their environmental mechanisms as described in ISO 14044 (see Fig. 1). Such a mechanism is the process for any given impact category, linking the LCI results to category indicators i.e., a sequence of effects that can cause a certain level of

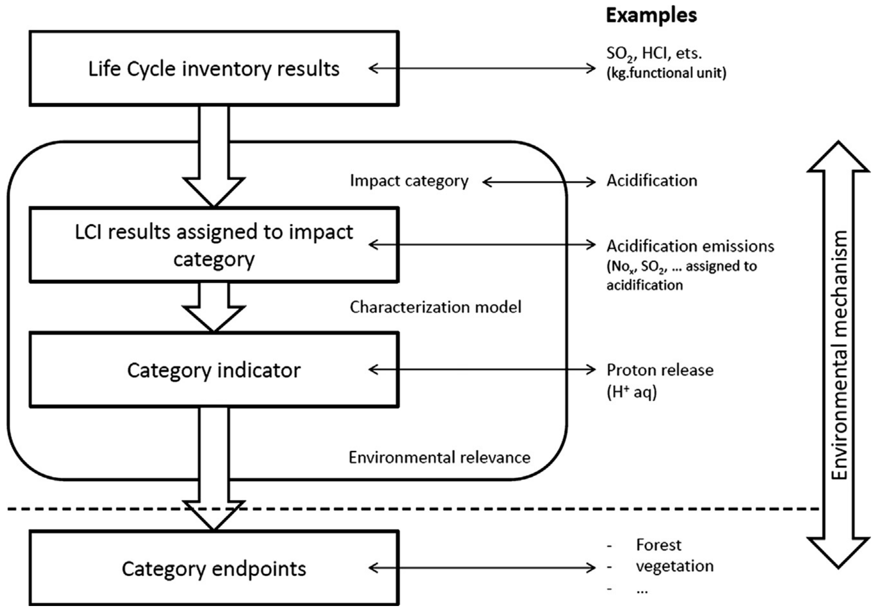

Fig. 1. Schematic presentation of an environmental mechanism underlying the modeling of impacts and damages in Life Cycle Impact Assessment (ISO 14044: 2006).

damage to the environment. These category indicators can be combined to more comprehensible and general indicators. Environmental mechanisms consist of sequences of complex conversion processes and the valuation factors used in environmental mechanisms are the main difference between LCA methods, as they may assign a different importance to the same physical values.

To quantify environmental impacts two approaches can be identified, namely the problem-oriented (midpoints) and damage-oriented (endpoints) ones, which can be combined as well [42]. The first group of methods uses values at the beginning or middle of the environmental mechanism. Impacts are classified on environmental themes such as global warming potential, acidification potential, ozone depletion potential, etc. This type of method generates a more complete picture of the ecological impacts, although the problem of incomparability may arise: is it worse to have 2 kg CO_2 eq. or 1 kg SO_2 eq.? Still these midpoints are important as they are directly linked to physical characteristics. The second group is at the end of the mechanism, where the midpoints are grouped into general damage categories such as human health, natural environment and resources, which eventually can be calculated into a single score. The results of the latter are easier to understand, but tend to be less transparent [43,44]. Another drawback of the endpoint approach is the use of more subjective factors in the conversion to general categories. This will entail greater uncertainties and affect the reliability of the results.

A weakness in current practice of LCA is that different methods applied to an identical case can generate different results e.g., a narrow scope carbon footprint study versus studies with a set of more differentiated impact indicators [44,45]. Various methods can assign a different importance to properties or impacts, which can result in other suggestions of action to reduce the ecological burdens [46]. Results of an LCA are no absolute values and therefore cannot serve as a certification on itself. They do not guarantee the sustainability of a product or service, but are valuable for the comparison of different products and processes. Comparing results of an LCA is only meaningful when the subjects fulfill exactly the same function in accordance with their goal and scope definitions.

Another weakness is the inability to investigate local impacts as, in general, environmental damage is calculated on global scale. In reality such assumptions are not always valid and emissions, for instance, can have a greater impact when they are released in vulnerable areas. A better solution is combine LCA with tools that are developed to assess local impacts, like Risk Assessment [9]. Additionally, local emissions can have also other consequences i.e., affect the indoor climate of a dwelling. From an environmental point of view, such emissions may deliver no significant contribution, but to ensure a healthy indoor climate within an LCA or other local damage, extra criteria should be integrated in the functional unit, often in order to comply with regulations [47].This shows once again the difficulty and importance to incorporate qualitative requirements into LCA.

4. Recent developments in the construction sector

4.1. Academic research

In industrial processes, LCA is widely spread and it is used frequently to evaluate the environmental impact of products and processes [48]. Buildings however are special products that differ thoroughly from these mostly controlled processes. In the construction industry, such a study is therefore on the average much more complex because of multiple issues: the long lifespan of the entire building (50–100 years [49–51]) and consequently a lower predictability of uncertainty variables and parameters (1), a shorter lifespan of some elements and components (2), the use of many different materials and processes (3), the unique character of each building (4), the varying distances to factories e.g., Canadian wood used in Belgian dwellings (5), the evolution of functions over time because of maintenance and retrofitting (6), etc. [42,50,52,53]. The long lifespan and dependence of user behavior thus require much more assumptions, coming with larger uncertainties and consequently influence the credibility of the results [54]. So since the building process is less standardized than industrial processes, such a Life Cycle Assessment is a challenging task.

A classification of existing studies could be done according to the magnitude of the subjects, going from materials to building components and finally the analysis of entire buildings [42]. Discussing the analysis of materials and components is beyond the scope of this review, however such studies have proved their value. When applying results of such studies, some things have to

be kept in mind. First, when comparing materials two possible alternatives have to fulfill the exact same function e.g., bricks and wood do not have the same structural characteristics. Studies on components, on the other hand, can partly counter this problem by incorporating additional requirements in their functional unit e.g., a cavity wall has to meet legal thermal or structural demands. Such studies are often useful during the design process, as at this stage many decisions are made about structural concepts and used materials, and they are strongly linked to the European policy e.g., the Integrated Product Policy, with tools as EPDs and Ecodesign [42].

In this paper, the main focus lies on LCAs of entire buildings. This way the contribution to the total impact of different products, processes and life cycle stages becomes more clear and environmental hotspots can be identified. The results reveal more about building concepts in general and less about the chosen materials. In these cases, the entire building is the functional unit, but with great differences in building properties, size, location, impact methods, etc. Therefore results are not directly comparable, but still trends can be identified. Table 1 contains an overview of published academic studies of LCAs of whole buildings and their main characteristics. A lot of these studies are simplified LCAs only discussing energy, especially the early studies. They are also known as a Life Cycle Energy Assessment (LCEA) and consider the cumulative energy demand during the different phases of the life cycle: embodied (production and construction), operational, demolition and recycling energy [89]. As stated by Huberman and Pearlmutter, this method is a single score indicator. Therefore the same remarks can be made as for the endpoint methods: it is easier to draw conclusions, but the results are much more subjective and less reliable [72,90]. A variation on this method is Life Cycle Exergy Assessment, developed by De Meester and Dewulf, which takes the quality of the energy into account [66,67]. Exergy is the work potential of an amount of energy with respect to its environmental conditions [91]. According to this method, the conversion of high grade energy (electricity) into low grade energy (heat) should be highly discouraged. Less frequent are the LCAs considering also other impact categories, which sometimes take the entire life cycle into account, but often only some life cycle stages. A wide variety of impact methods is used, from midpoint to endpoint (e.g. CML, Eco-indicator 99, Carbon footprint), sometimes a set of different methods is applied or results are examined whether they comply with policy targets. A detailed discussion on these impact methods is beyond the scope of this review, nevertheless in Table 1 the applied impact method is represented for each of the studies (an overview can be found in [92]). As cited in Section 3, from a methodological point of view, a subdivision can be made between damage- and problem-oriented methods. In practice however, as can be seen at the presented studies, there appears to be a more complex variety, where the wide range of generally accepted methods sometimes are combined with specifically developed variants. The most basic studies are the ones using only results directly related to impact categories, without any grouping nor weighting however as mentioned before, they are also the most objective (1). Next are the analyses calculating a selection of possible impacts of a life cycle e.g., the cumulative energy or exergy demand and carbon footprints (2), as discussed before. A third group comprises the distance-to-target-methods evaluating sustainability related to fixed or legal policy targets (3) e.g., BYKR and Ecological Scarcity 2006. Some other methods are strongly simplified and thus have to be interpreted with care, especially if they are widely spread (4) e.g., Ecolizer 2.0. The more commonly used and generally accepted methods are the damage-oriented ones (5) e.g., Eco-Indicator 99, EPS, EDIP, external costs, and the problem oriented (6), e.g. CML 2001. Finally, one of the newer methods is Recipe, combining both the midpoint and the endpoint level and based on Eco-Indicator 99 and CML-IA (7); yet, it has not been utilized within the present review [92–94].

Before looking at the results of the studies, some remarks must be made, since the characteristics of the cases differ sometimes substantially. First, not all studies have the same coverage of the life cycle. The following aspects are sometimes excluded: transportation, waste factors, maintenance, water use, etc. Also the accuracy differs i.e., some studies are coarse and not as detailed which only take the most obvious products and processes into account; therefore a distinction can be made between detailed LCAs and screening LCAs as well, not based on methods, but on the level of detail. Next, there is a wide variety in the methods used. Fourth, various topics were subject of research. Most of the studies consider residential buildings, but schools and office buildings have been investigated as well. The cases differ in construction period, level of technology or building concept. Finally, not always all phases of the life cycle have been included.

In addition, some extra steps can be included besides the mandatory steps of an LCA, namely a sensitivity check and an uncertainty analysis. The first one is to verify the sensitivity of significant data elements of the results by varying parameters, choice of data, assumptions or impact assessment methods to check if the results are still valid. If not, this has to be documented. Another optional step is to investigate uncertainties of the life cycle inventory which can be divided into different categories: variability and stochastic error of the figures which describe the inputs and outputs due to e.g., measurement uncertainties, process specific variations, temporal variations, etc. (1), appropriateness of the data (2), model uncertainty e.g., due to inappropriate descriptions of processes (3) and finally neglecting the important flows (4) [95]. Uncertainties related to deviations of the first category are inherent to every practical process and data quality indicators are sufficiently available, for example in the Ecoinvent database; however only the study of Blengini and Di Carlo included this step [43]. The other three types of uncertainties are difficult to calculate and should be reduced by collecting additional and more precise data.

As mentioned before, the parameters of the existing research vary substantially, but nevertheless some common trends can be indicated. One of the conclusions of almost every research is the dominance of the use phase, especially due to energy consumption of heating and cooling. The share of the use phase of standard houses is in the range of 60–90% of the total environmental burdens, mainly with a contribution to global warming potential [55,74]. Even in very different climates this conclusion appears to be valid, as studies in Nordic and Mediterranean countries come to similar results [55,77]. A common conclusion of these studies is therefore the necessity of reducing the need for heating and/or cooling by improving insulation, improving air-tightness and controlling ventilation. Some of these aspects can be found in the European Policy, which is strongly focused on reducing energy consumption (EPBD 2010) [3].

The conclusions mentioned in the previous paragraph are generally taken into account during the design and execution of low-energy houses whereby the energy use can strongly be reduced. Several studies of this kind of buildings have been carried out which often also analyze the impact of optimization suggestions, however only on dwellings so far. Blengini and Di Carlo investigated a low energy dwelling in Italy. Although the energy consumption was ten times lower than the reference standard house, the total environmental impact was only reduced by a factor 2.1 [43]. So when the energy use is pushed back, the other phases of the life cycle are growing in relative importance, like for example construction methodology, the choice of materials and end-of-life scenarios. Huberman reaches similar conclusions: if

operational energy (use) decreases, embodied energy (materials) increases relatively, a trend which occurs more often since industrialization [72]. Citherlet and Defaux mention that it is only relevant to pay much attention to the impact of the production and end-of-life phase (referred to as '*indirect impacts*') when the yearly energy consumption is below 150 MJ/m² [64].

As new buildings are designed more energy-efficiently, a next step in research is to pay more attention to the growing relevance of the other phases. Thormark focused on the recycling potential and the concept '*Design for disassembly*', while Blengini examined the demolition of a flat to verify and/or complete the literature data [45,62,84,85]. Both studies show the benefits of reuse in the first place, which is slightly superior to recycling, yet they do have reservations about the feasibility of reuse on a large scale since it requires major changes from current practice and may not be profitable. Goverse et al. describe problems of a switch-over of existing economic structures, especially in this case, where large changes in technical and network dimensions are necessary [96]. In line is the research of Erlandsson and Levin focusing on the benefits of renovation, a construction method that is gaining importance as can be seen in Belgian statistics: the share of building permits for renovations increased with more than 30% over the last 15 years [97]. Renovation is generally more eco-friendly, but urban regulations are a limitation that often do not allow all optimal measures, especially if they occur on the outside of the building, for example additional insulation [68].

Complementary to the previous paragraph is the static and inflexible approach of the calculation of the use phase of most studies. In the best case, and the most common, replacements of components are included after the predicted technical lifespan by the same components. In reality however, they are more likely to be replaced by technologically more advanced components with a better performance. In addition, during the lifespan of a building, more radical renovations will often be carried out to meet current (or future) comfort demands [68,98]. These aspects influence the use phase, particularly when they improve the energetic performance and therefore they should be included. However LCA is a static tool, this drawback can be overcome by including scenarios, as described in the study of Van Nunen [98]. In this study different scenarios for renovation cycles have been developed and they provide a better understanding of the importance of maintenance and refurbishments. Such an approach is also useful to indicate priorities for renovating a building, as described in the study of Verbeeck and Hens, which compares i.e., scenarios for optimizing new buildings with scenarios for renovations [99].

The international nature of research on LCA in combination with local production chains makes the comparison more difficult. The regional electricity mix, for instance, has a great influence on the impact of the use phase [56]. The study of Ortiz-Rodríguez et al. compares a dwelling in Spain with one in Colombia [78]. In this study, 20% of the total required energy is covered by electricity, of which the production differs significantly between the two countries. The environmental burden of electricity production is twice as large in Spain as in Colombia for most of the impact categories, mainly due to the larger share of hydropower.[1] Another example is the study of Braet, that compares container pipeline transport versus road transport. As sensitivity analysis, different scenarios for electricity production are included and they have a great effect on the results, also strongly related to impact assessment methods. In the coal energy scenario the road concept performs better than the pipeline concept using the ReCiPe or IPCC GWP 100a method. In the natural gas scenario both concepts have an equal environmental impact for all available methods used. In all other electricity production scenarios, such as nuclear energy, the pipeline concepts outperforms the road concept for all available impact assessment methods used [48].

Cuéllar-Franca and Azapagic investigate also the influence of the choice of functional unit, which is in most studies the entire building or net habitable floor area. This study however compares three dwelling type alternatives (detached, semi-detached and terraced), each with their typical size and characteristics. The number of inhabitants is assumed to be the average UK household size, consisting of 2,3 people. When looking to the impact per square meter as functional unit, the detached house has the lowest impacts per unit of floor area. This is mainly due to the impacts related to the household size, such as water consumption, energy for cooking, etc. which is the same for all three dwelling type alternatives. When looking at impact per inhabitant however, the smallest and most compact alternative (terraced) has the lowest impact [80].

Not only energetic but also structural concepts have been compared, mainly renewable (wood) versus non-renewable materials (masonry, concrete, steel) in the context of low-energy dwellings. Most research assigns better results to wooden structures [65,70,76]. Wood is easier to manipulate and CO_2 neutral, while production of steel and concrete induces more burdens due to production and processing and has a higher embodied energy. However, the use of timber frames is limited to buildings up to three floors [65]. Only the research of Marceau and VanGeem comes to opposite conclusions, with a preference for concrete structures, mainly because of the higher land use of wood [75].

Another frequent conclusion is the minor importance of the transportation of materials during construction. Almost all the research included this aspect, but as building materials are often locally produced, the travel distances and associated impacts are limited, for example 1% or less according to Adalberth and Ortiz et al. [55,77]. Even when some parts are transported over a long distance, the associated impact does not play a major role. Designers and public administrators participating in the Italian study by Blengini and Di Carlo on a low energy house were surprised by the minor contribution of transportation, as it was feared that triple glazed windows imported from Germany and cork slab transported over long distances by truck and ship would compromise the environmental performances [43]. Only when almost all materials are transported over a great distance, transportation becomes an issue of concern, which can be seen in the research of Chen et al. Materials of two analyzed office buildings in Hong Kong are mostly imported, often overseas, which can be seen in the contribution of transportation of 7% to the total environmental burdens [63].

4.2. Regulatory developments

The previous sections demonstrate that in current academic practice, only general trends can be derived from the examined studies. However buildings are not directly comparable. All these studies are executed according to the framework described in the ISO 14040 series, which is applicable to all types of studies. As life-cycle thinking becomes more integrated in policy and marketing, there will be a need for a more delineated framework, specifically for buildings. As mentioned in Section II, international organizations like ISO and CEN are working on the standardization of LCAs in the construction sector in order to improve the comparability of such studies. A main goal of the latter is documenting the environmental performance of a building for use in e.g., declaring environmental performance, labeling and marketing. As stated by

[1] The authors state that a dual approach can be desirable: one for elaborating actual optimizations – local averages (attributional) or marginal suppliers (consequential) – and one to ensure comparability with other scientific studies—continental or global averages. This could prevent wrong extrapolating of specific results.

CEN TC 350 in EN 15978:2011, 'the *purpose of this European Standard is to provide calculation rules for the assessment of the environmental performance of new and existing buildings*' [100]. These rules consist in the description of functional equivalent, system boundaries, procedures to be used for the inventory analysis, a list of environmental indicators and procedures for the calculation of the impact categories, rules for reporting and communicating results, etc. This framework is very similar to the one of EPDs, which encourages and facilitates the incorporation of results of external studies. The previously mentioned regulation is part of a larger set of standards, also focusing on other aspects of sustainability like social and economic performance, both at the building and product level.

Such rules for standardization can be a limitation as well, by excluding environmental indicators which are integrated in commonly used impact methods. For example the successor of Eco-indicator 99, ReCiPe, that combines midpoints and endpoints, takes resource depletion and land use into account, impact categories that are excluded in the new standards [93,100]. Since this is a popular series of methods, many (existing) studies are therefore not in line with the new standards. The exclusion of land use can affect results significantly, especially if a lot of wood is used e.g., when comparing timber frame with heavyweight constructions. Guardigli et al. investigated a wood structure in Italy and states the main environmental impact is due to the land use of wood [71]. A possible solution is to follow the new standards, but supplement them with other relevant impact categories.

5. Discussion and limitations

This review focuses on case based LCA studies of entire buildings, being a great tool to investigate building concepts and to support decision-making to reduce environmental burdens. Nevertheless the LCA methodology has some inherent limitations, consequently results should be interpreted and used with care. First, the cases are difficult to compare because of their specific properties like lay-out, climate, comfort requirements, local regulations, etc. The widespread estimations of the lifespan of buildings is a second limitation. These two limitations can be partly overcome by calculating the annual burdens per square meter useful floor surface or per person, still other aspects of the studies can differ e.g., system boundaries, assumptions, level of detail, LCIA methods, etc. Next, LCA is merely a model and simplification of reality, so assumptions have to be made that can generate uncertainties on different levels: model, scenario and parameter uncertainties [101]. The first two aspects are difficult to process statistically and are often excluded, but with the latter this is possible as data quality indicators are available for all materials and processes in the Ecoinvent database (see also section IV). Parameter uncertainty is also often enhanced by data gaps, resulting in less accurate data to be used. When considering the variability and stochastic error of the figures, the reliability is enhanced but the interpretation has to be performed by using probability statements, which are less common but still useful conclusions can be drawn.

As mentioned before, the use phase of buildings is the dominant factor of the environmental burdens over the entire life cycle, especially through the high energy consumption. The burdens of this phase are based on estimations, taking average values of the whole society into account. Since individual inhabitant behavior is difficult to predict, it is also an issue of concern when considering the reliability of any conclusion on energy consumption. This limits the practical importance of LCA, no matter how accurate calculations may have been carried out. Research concluded that many efficiency improvements do not reduce energy consumption as much as predicted. As they make energy services cheaper, the demand for these services will increase. For example, if a dwelling is well insulated, residents are more likely to heat up the spaces above the calculated temperature, since this entails only a limited additional cost. This psychological phenomena is called the rebound effect and until now this has not been taken into account [41]. A stochastic approach based on real data could partly counter this problem; however, rebound effects will always occur as economic savings will trigger other (non-building related) expenditures which of course entail also environmental burdens. An extra difficulty is the fact that user behavior and consumption habits are often regionally defined, as investigated by Ortiz-Rodríguez et al. The difference in environmental impact between a Spanish and Columbian dwelling is partly caused by such social differences [78].

Another drawback of current LCA practice within the construction sector is the isolated approach of environmental issues. Often the focus is limited to the search for environmental optima, but without linking it to other aspects. For example, LCA does not take into account any quality, energetic, structural nor esthetic requirements. According to Allacker, the design plays a major role in the environmental profile, but this has been barely investigated yet [57]. Also financial feasibility is hardly ever taken into account, although ready-to-use tools are available, for example Life Cycle Costing. Only a few researchers include financial and ecological aspects and give a more complete picture, like Allacker, Blanchard and Reppe, and Verbeeck [57,61,99]. Although new regulations and frameworks have been worked out for assessing all aspects of sustainability, at the moment they are not frequently implemented.

6. Research opportunities

The growing importance of LCA as a scientific tool to evaluate environmental burdens is a positive trend; however there are still many research opportunities and areas to improve current practice. The construction sector causes unwanted environmental effects, but economic costs to repair or avoid them rarely appear in the resulting prices of goods and services. Internalization is nevertheless crucial if our society wishes to enhance its sustainability on the long term, without burdening future generations. As this is currently not occurring systematically, it is a challenge to reflect environmental costs of building materials and processes in their sales prices. This way manufacturers or service providers should be held responsible to repair or counter the environmental effects of their production processes. The link between environmental impact and cost implications needs to be established and clearly communicated.

Currently the main focus is at energy reduction, both in policy and research. However, the research of Allacker states that other aspects may play an important role too, like water consumption. The impact of water consumption equals 18% for a non-insulated dwelling and up to 88% for a low-energy dwelling of the burdens of heating. As reducing energy consumption is starting to get established, it is possible to pay increased attention to other issues. So now, besides the impact of materials and end-of-life treatment, reducing the water consumption of households is gaining importance too [57]. The reduction of water consumption will have to be examined more thoroughly in future research.

Another conclusion of the same research is the importance of architectural design, which has often more effect than purely technological improvements. Solar gains, orientation and compactness are quickly overlooked, since they are very site dependent and subject to urban regulations. A set of instructions, guidelines and the incorporation within the urban policy could

trigger a positive evolution towards a more sustainable building stock.

The fourth research opportunity is related to the commonly used data, which are mostly deterministic values. Although these values often come from averages, more research is needed to evaluate if they are representative for a specific case study. A study of Aktas and Bilec investigates the influence of the assumptions on the functional lifetime: they consider the lifetime as a distribution, compared to the deterministic derived from average values [102]. They state that the use of distributions instead of deterministic values for lifetime of products and buildings improves accuracy of the study and make results more objective and comparable. This approach has a huge potential for improving the reliability of LCA results, by expanding the use of distributions. Aspects as energy and water use, transport loads and distances, cutting waste, etc. should be evaluated by using probability density distributions reflecting the effective variability of parameters in practice. Especially all aspects related to the dominant phases of the life cycle (energy, water) can have a great influence, although a major problem can be the lack of data.

The last opportunity is to incorporate other methods to assess the influence of the lifespan of components e.g., the factor method [103]. During the lifespan of an entire building, many components have to be replaced. In practice such replacements do not always occur as the technical lifespan is expired as usually assumed in current practice in LCAs. The factor method takes aspects as local setting, parameters and quality of execution into account to adjust the technical lifespan and convert it to more case specific number (this can both shorten or prolong the expected service life). This can provide a more precise image in terms of practice of the contribution of maintenance and replacements, however the same remarks can be made as in the previous paragraph: the factor method works with deterministic values, which should be replaced by stochastic distributions. Van Nunen tried this, but a lack of data prevented the development of a global applicable tool [98].

7. Conclusion

This analysis of case studies indicates a growing attention for sustainability in the construction sector. Current regulatory frameworks are developed to facilitate the implementation of the assessment of environmental performances. Despite some limitations of the LCA technique, it is still a powerful and science-based tool to evaluate the environmental impacts. The listed cases focus on analysis of whole buildings, so environmental hotspots can be indicated and priorities for action can be defined. A recurrent conclusion is the dominance of the use phase, especially in conventional buildings, mainly caused by the need for heating and cooling. As a consequence new building concepts, focusing on energy efficiency, have arisen. Within the life cycle of the latter, there occurs a shift of environmental burdens from use phase to construction, materials and end-of-life treatment. As well-insulated buildings will become the new standard, these other issues deserve more attention. Until now, European policy focused mainly on controlling energy consumption, but as illustrated by this review, new fields of action emerge, like for example controlling and reducing water consumption and paying more attention to a smart design. To increase the reliability of results, there should also be more attention for the use of probability density distributions instead of deterministic values for representing independent variables and parameters. Finally, to enhance a sustainable society, people should be aware of the ecological impact of products and services. This could be achieved by internalization, so the environmental effects would be reflected in market prices.

References

[1] Ewing B, Moore D, Goldfinger S, Oursler A, Anders Reed A, Wackernagel M. Ecological footprint atlas 2010. Oakland, California, USA: Global Footprint Network; 2010.

[2] The European Parliament. Directive 2002/91/EC of the European Parliament and of the Council on the energy performance of buildings. Communities 2003;L(1):65–71.

[3] The European Parliament. Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings (recast). Official Journal of the European Union 2010:153/13–35 〈http://europa.eu/legislation_summaries/internal_market/single_market_for_goods/construction/en0021_en.htm〉.

[4] Hens H, Janssens A. Gebouwen, wonen en energie in: Energie vandaag en morgen—Beschouwingen over energievoorziening en gebruik. Leuven, Belgium: ACCO; 2005.

[5] IEA. Energy policies of IEA countries. Belgium 2009 review, Paris; 2009.

[6] Audenaert A, De Cleyn SH, Vankerckhove B. Economic analysis of passive houses and low-energy houses compared with standard houses. Energy Policy 2008;36(1):47–55.

[7] Audenaert A, De Cleyn SH. Cost benefit analysis of Passive houses and low-energy houses compared to standard houses. International Journal of Energy 2010;4(3):46–53.

[8] Buyle M, Audenaert A, De Cleyn SH. Material optimization of low-energy flats using the LCA Eco-indicator 99 method: impact of materials and EOL. In: Proceedings of the 2nd international conference of the institute for environment, engineering, economics and applied mathematics: urban sustainability, cultural sustainability, green development, green structures and clean cars (USCUDAR 2011). Prague, Czech; September 26–28 2011. p. 6.

[9] Finnveden G, Moberg Å. Environmental systems analysis tools—an overview. Journal of Cleaner Production 2005;13:1165–73.

[10] ISO 14040—Environmental management—life cycle assessment—principles and framework. Geneva, Switzerland: International Organisation for Standardization; 2006.

[11] Guinée JB, Heijungs R, Huppes G, Zamagni A, Masoni P, Buonamici R, et al. Life cycle assessment: past, present, and future. Environmental Science and Technology 2011;45(1):90–6.

[12] Bekker P. A life-cycle approach in building. Building and Environment 1982;17(1):55–61.

[13] Guinee JB, Udo De Haes HA, Huppes G. Quantitative life cycle assessment of products: 1:goal definition and inventory. Journal of Cleaner Production 1993;1(1):3–13.

[14] Fava JA, Denison R, Jones B, Curran MA, Vigon B, Selke S, et al. A technical framework for life-cycle assessments. Washington: SETAC; 1991.

[15] Life-cycle assessment. In: Proceedings of a SETAC-Europe workshop on environmental life cycle assessment of products December 2−3 1991, Leiden; 1992.

[16] Jensen AA, Hoffman L, Møller BT, Schmidt A, Christiansen K, Elkington J, et al. Life cycle assessment. A guide to approaches, experiences and information sources. Copenhagen, Denmark: European Envirionment Agency; 1998.

[17] Nordic Council of Ministers. Product life cycle assessment—principles and methodology. Copenhagen: Nordic Council of Ministers; Stockholm: Nordic Council; 1992.

[18] Heijungs R, Guinee JB, Huppes G, Lankreijer RM, Udo de Haes HA, Wegener Sleeswijk A. et al. Environmental life cycle assessment of products. Guide & Backgrounds—October 1992, no. October. Leiden, The Netherlands: Center of Environmental Science, Leiden University; 1992.

[19] Consoli F, Allen D, Boustead I, de Oude N, Fava J, Franklin W, et al. Guidelines for life-cycle assessment: a "code of practice". 1e ed. Brussels, Belgium: SETAC-Europe; 62.

[20] ISO 14040—Environmental management—life cycle assessment—principles and framework. International Organisation for Standardization; 1997.

[21] Commission of the European Communities. Integrated product policy: building on environmental life-cycle thinking. Journal of International Wildlife Law Policy 2003;12(1):30.

[22] Communication from the commission to the council and the European Parliament—integrated product policy—building on environmental life-cycle thinking—COM(2003) 302 final; 2003.

[23] Wolf M-A, Pant R, Chomkhamsri K, Sala S, Pennington D. The International Reference Life Cycle Data System (ILCD) handbook. European Commission, Joint Research Centre, Institute for Environment and Sustainability; 2012.

[24] European Commission - Joint Research Centre - Institute for Environment and Sustainability. ILCD handbook: general guide to life cycle assessment–detailed guidance. 1st ed. Luxembourg: Publications Office of the European Union; 417.

[25] UN environment program life cycle initiative website. Available from: 〈http://lcinitiative.unep.fr/〉.

[26] Jolliet O, Dubreuil A, Gloria T, Hauschild M. Progresses in life cycle impact assessment withing the UNEP/SETAC life cycle initiative. The International Journal of Life Cycle Assessment 2005;10(6):447–8.

[27] ISO 14025—Environmental labels and declarations—type III environmental declarations—principles and procedures. International Organization for Standardization; 2006.

[28] (WTCB) Putzeys K. Milieurelevante productinformatie: stand van zaken in België en europa. WTCB-Dossiers—Nr. 1/2007—Katern nr. 3; 2007. p. 9.
[29] Fava JA. Will the next 10 years be as productive in advancing life cycle approaches as the last 15 years? The International Journal of Life Cycle Assessment 2006;11(1):6–8.
[30] Setac. Life-cycle assessment in building and construction: a state-of-the-art report; 2003.
[31] Available from: 〈http://www.iso.org〉; 2012 [accessed 11.05.12].
[32] Available from: 〈http://www.cen.eu〉; 2012 [accessed 11.05.12].
[33] Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A. Handbook on life cycle assessment: operational guide to the ISO standards. Dordrecht, The Netherlands: Kluwer Academic Publisher; 2002.
[34] ISO 14044—Environmental management—life cycle assessment—requirements and guidelines. International Organisation for Standardization; 2006.
[35] Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T, et al. Life cycle assessment part 1: framework, goal and scope definition, inventory analysis, and applications. Environment International 2004;30 (5):701–20.
[36] S. Reiter, Life cycle assessment of buildings—a review. Sustainability workshop and third plenary meeting. Brussels, Belgium; 07/07/2010. p. 1–19.
[37] Curran M, Mann M, Norris G. The international workshop on electricity data for life cycle inventories. Journal of Cleaner Production 2005;13(8): 853–62.
[38] Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, et al. Recent developments in life cycle assessment. Journal of Environmental Management 2009;91:1–21.
[39] Tillman A. Significance of decision-making for LCA methodology. Environmental Impact Assessment Review 2000;20:113–23.
[40] Weidema BP. Market information in life cycle assessment. Copenhagen: Environmental Project no. 863. Danish Environmental Protection Agency; 2003.
[41] Greening LA, Greene DL, Difiglio C. Energy efficiency and consumption—the rebound effect—a survey. Energy Policy 2000;28(6–7):389–401.
[42] Ortiz O, Catsells F, Sonnemann G. Sustainability in the construction industry: a review of recent developments based on LCA. Construction and Building Materials 2009;23:28–39.
[43] Blengini GA, Di Carlo T. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. Energy and Buildings 2009;42:869–80.
[44] Finnveden G, Eldh P, Johansson J. Wheighting in LCA based on ecotaxes. development of a mid-point method and experiences from case studies. The International Journal of Life Cycle Assessment 2006;11(1):81–8.
[45] Thormark C. Environmental analysis of a building with reused building materials. The International Journal of Low Energy and Sustainable Buildings 2000;1. (18 pp.) 〈http://dspace.mah.se/bitstream/handle/2043/9844/staffanstorp.pdf?sequence=1〉.
[46] Toller S, Wadeskog A, Finnveden G, Malmqvist T, Carlsson A. Energy use and environmental impacts of the Swedish building and real estate management sector. Journal of Industrial Ecology 2011;15(3):394–404.
[47] Peuportier BLP. Life cycle assessment applied to the comparative evaluation of single family houses in the French context. Energy and Buildings 2001;33:443–50.
[48] Braet J. The environmental impact of container pipeline transport compared to road transport. Case study in the Antwerp Harbor region and some general extrapolations. The International Journal of Life Cycle Assessment 2011;16(9):886–96.
[49] Satori I, Hestnes AG. Energy use in the life cycle of conventional and low-energy buildings: a review article. Energy and Buildings 2007;39:249–57.
[50] Ramesh T, Prakash R, Shukla KK. Life cycle energy analysis of buildings: an overview. Energy and Buildings 2010;42:1592–600.
[51] Buyle M, Braet J, Audenaert A. Review on LCA in the construction industry: case studies. In: Proceedings of the 3rd INEEE conference: energy, environment, devices, systems, communications, computers (INEEE '12). Rovaniemi, Finland; April 18–20 2012.
[52] Bribián IZ, Usón AA, Scarpellini S. Life cycle assessment in buildings: state-of-the-art and simplified LCA methodology as a complement for building certification. Building and Environment 2009;44:2510–20.
[53] Sharma A, Saxena A, Sethi M, Shree V. Life cycle assessment of buildings: a review. Renewable and Sustainable Energy Reviews 2011;15(1):871–5.
[54] Blom I, Itard L, Meijer A. Environmental impact of building-related and user-related energy consumption in dwellings. Building and Environment 2011;46(8):1657–69.
[55] Adalberth K. Energy use during the life cycle of single-unit dwellings: examples. Building and Environment 1997;32(4):321–9.
[56] Adalberth K, Almgren A, Petersen EH. Life cycle assessment of four multi-family buildings. The International Journal of Low Energy and Sustainable Buildings 2001;2:1–21.
[57] Allacker K. Sustainable building, the development of an evaluation method. Leuven, Belgium: Katholieke Universiteit Leuven; 2010.
[58] Arena A, de Rosa C. Life cycle assessment of energy and environmental implications of the implementation of conservation technologies in school buildings in Mendoza-Argentina. Building and Environment 2003;38 (2):359–68.
[59] Asif M, Muneer T, Kelley R. Life cycle assessment: a case study of a dwelling home in Scotland. Building and Environment 2007;42(3):1391–4.
[60] Audenaert A, De Cleyn SH, Buyle M. LCA of low-energy flats using the eco-indicator 99 method: impact of insulation materials. Energy and Buildings 201268–73.
[61] Blanchard S., Reppe P. Life cycle analysis of a residential home in Michigan; 1998.
[62] Blengini GA. Life cycle of buildings, demolition and recycling potential: a case study in Turin. Building and Environment 2009;44:319–30.
[63] Chen TY, Burnett J. Analysis of embodied energy use in the residential building of Hong Kong. Energy 2001;26(4):323–40.
[64] Citherlet S, Defaux T. Energy and environmental comparison of three variants of a family house during its whole life span. Building and Environment 2007;42(2):591–8.
[65] Cole R, Kernan PC. Life-cycle energy use in office buildings. Building and Environment 1996;31(4):307–17.
[66] De Meester B, Dewulf J, Verbeke S, Janssens A, Van Langenhoven H. Exergetic life-cycle assessment (ELCA) for resources consumption evaluation in the built environment. Building and Environment 2009;44:11–7.
[67] Dewulf J, Van der Vorst G, Versele N, Janssens A, Van Langenhove H. Quantification of the impact of the end-of-life scenario on the overall resource consumption for a dwelling house. Resources, Conservation and Recycling 2009;53(4):231–6.
[68] Erlandsson M, Levin P. Environmental assessment of rebuilding and possible performance improvements effect on a national scale. Building and Environment 2005;40(11):1459–71.
[69] Fay R, Treloar G, Iyer-raniga U. Life-cycle energy analysis of buildings: a case study. Building Research and Information 2000;28(1):31–41.
[70] Gerilla G, Teknomo K, Hokao K. An environmental assessment of wood and steel reinforced concrete housing construction. Building and Environment 2007;42(7):2778–84.
[71] Guardigli L, Monari F, Bragadin MA. Assessing environmental impact of green buildings through LCA methods: a comparison between reinforced concrete and wood structures in the European context. Procedia Engineering 2011;21:1199–206.
[72] Huberman N, Pearlmutter D. A life-cycle energy analysis of building materials in the Negev desert. Energy and Buildings 2008;40(5):837–48.
[73] Junnila S. Life cycle assessment of environmentally significant aspects of an office building. Nordic Journal of Surveying and Real Estate Research - Special Series 2004;2:81–97.
[74] Kofoworola OF, Gheewala SH. Environmental life cycle assessment of a commercial office building in Thailand. The International Journal of Life Cycle Assessment 2008;13(6):498–511.
[75] Marceau ML, VanGeem M. Comparison of the life cycle assessments of an insulating concrete form house and a wood frame house. Journal of ASTM International 2006;3(9):1–11.
[76] Mithraratne N, Vale B. Life cycle analysis model for New Zealand houses. Building and Environment 2004;39:483–92.
[77] Ortiz O, Bonnet C, Bruno JC. Sustainability based on LCM of residential dwellings: a case study in Catalonia, Spain. Building and Environment 2009;44.
[78] Ortiz-Rodríguez O, Castells F, Sonnemann G. Life cycle assessment of two dwellings: one in Spain, a developed country, and one in Colombia, a country under development. The Science of the Total Environment 2010;408(12): 2435–43.
[79] Venkatarama Reddy B, Jagadish KS. Embodied energy of common and alternative building materials and technologies. Energy and Buildings 2003;35(2):129–37.
[80] Cuéllar-Franca RM, Azapagic A. Environmental impacts of the UK residential sector: life cycle assessment of houses. Building and Environment 2012;54: 86–99.
[81] Rossi B, Marique A-F, Glaumann M, Reiter S. Life-cycle assessment of residential buildings in three different European locations, basic tool. Building and Environment 2012;51:395–401.
[82] Scheuer C. Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. Energy and Buildings 2003;35(10):1049–64.
[83] Suzuki M, Oka T. Estimation of life cycle energy consumption and CO2 emission of office buildings in Japan. Energy and Buildings 1998;28(1): 33–41.
[84] Thormark C. A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. Building and Environment 2002;37:429–35.
[85] Thormark C. The effect of material choice on the total energy need and recycling potential of a building. Building and Environment 2006;41: 1019–26.
[86] Wu H, Yuan Z, Zhang L, Bi J. Life cycle energy consumption and CO_2 emission of an office building in China. The International Journal of Life Cycle Assessment 2011;17(2):105–18.
[87] Xing S, Xu Z, Jun G. Inventory analysis of LCA on steel- and concrete-construction office buildings. Energy and Buildings 2008;40(7): 1188–93.
[88] Zimmermann M, Althaus H-J, Haas A. Benchmarks for sustainable construction. Energy and Buildings 2005;37(11):1147–57.
[89] Gustavsson L, Joelsson A. Life cycle primary energy analysis of residential buildings. Energy and Buildings 2010;42(2):210–20.

[90] Dixit MK, Fernández-Solís JL, Lavy S, Culp CH. Need for an embodied energy measurement protocol for buildings: a review paper. Renewable and Sustainable Energy Reviews 2012;16(6):3730–43.
[91] Kotas TJ. The exergy method of thermal plant analysis. Malabar: Krieger Publishing Company; 1995.
[92] Frischknecht R, Jungbluth N, Althaus H, Bauer C, Doka G, Dones R. et al. Implementation of life cycle impact assessment methods: data v2.0. Ecoinvent report no. 3. Swiss centre for Life Cycle Inventories. Dübendorf, Switzerland; 2007.
[93] Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, van Zelm R. ReCiPe 2008: a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; 2012.
[94] Pennington DW, Potting J, Finnveden G, Lindeijer E, Jolliet O, Rydberg T, et al. Life cycle assessment part 2: current impact assessment practice. Environment International 2004;30(5):721–39.
[95] Frischknecht R, Jungbluth N, Althaus H, Doka G, Dones R, Heck T, et al. Overview and methodology: ecoinvent report No. 1. Dübendorf, Switzerland: Swiss Centre for Life Cycle Inventories. 2007.
[96] Goverse T, Hekkert MP, Groenewegen P, Worrel E, Smits REHM. Wood innovation in the residential construction sector; opportunities and constraints. Resources, Conservation and Recycling 2001;34:53–74.
[97] Bouwvergunningen (1996–2010), Statistics Belgium. Available from: ⟨http://statbel.fgov.be/nl/statistieken/cijfers/economie/bouw_industrie/bouwvergunning/⟩. [accessed 09.01.12].
[98] van Nunen H. Assessment of the sustainability of flexible building—the improved factor method: service lift prediction of buildings in the Netherlands, applied to life cycle assessment. Boxtel: Uitgeverij Æneas; 224.
[99] Verbeeck G, Hens H. Optimisation of extremely low energy residential buildings. Leuven, Belgium: Katholieke Universiteit Leuven; 2007.
[100] EN 15978:2011—Sustainability of construction works—assessment of environmental performance of buildings—calculation method; 2011. p. 59.
[101] Buyle M, Audenaert A, Braet J. Life Cycle Assessment as a tool to improve sustainability of the Flemish residential construction sector: methodology for simplified designs. In: Proceedings of the 8th IASME/WSEAS international conference on energy, environment, ecosystems and sustainable development (EEESD'12). Faro, Portugal; May 2–5 2012.
[102] Aktas CB, Bilec MM. Impact of lifetime on US residential building LCA results. The International Journal of Life Cycle Assessment 2011;17(3):337–49.
[103] ISO 15686-1—Buildings and constructed assets—service life planning—Part 1: general principles. International Organisation for Standardization; 2000.